Chemodynamical Modeling of Drawf Galaxy Evolution

[1]P. Berczik, [2]G. Hensler, [2]Ch. Theis and [3]R. Spurzem

[1]Main Astronomical Observatory, Ukrainian National Academy of Sciences
Zabolotnoho Str., 27, 03680, Kiev, Ukraine. E-mail: berczik@mao.kiev.ua

[2]Institut für Theoretische Physik und Astrophysik, University of Kiel,
Olshausenstr. 40, 24098 Kiel, Germany.

[3]Astronomisches Rechen-Institut,
Mönchhofstraße 12-14, 69120 Heidelberg, Germany.

Abstract

We present our recently developed 3-dimensional chemodynamical code for galaxy evolution. It follows the evolution of all components of a galaxy such as dark matter, stars, molecular clouds and diffuse interstellar matter (ISM). Dark matter and stars are treated as collisionless N-body systems. The ISM is numerically described by a smoothed particle hydrodynamics (SPH) approach for the diffuse (hot) gas and a sticky particle scheme for the (cool) molecular clouds. Additionally, the galactic components are coupled by several phase transitions like star formation, stellar death or condensation and evaporation and condensation processes within the ISM. As an example here we present the dynamical, chemical and photometric evolution of a star forming dwarf galaxy with a total baryonic mass of $2 \times 10^9 M_\odot$.

Keywords: *computational methods: SPH, chemodynamics – evolution of galaxies: dwarf galaxy evolution*

1. Introduction

Since several years smoothed particle hydrodynamics (SPH, Monaghan (1992)) calculations have been applied successfully to study the formation and evolution of galaxies. Its Lagrangian nature as well as its easy implementation together with standard N-body codes allows for a simultaneous description of complex

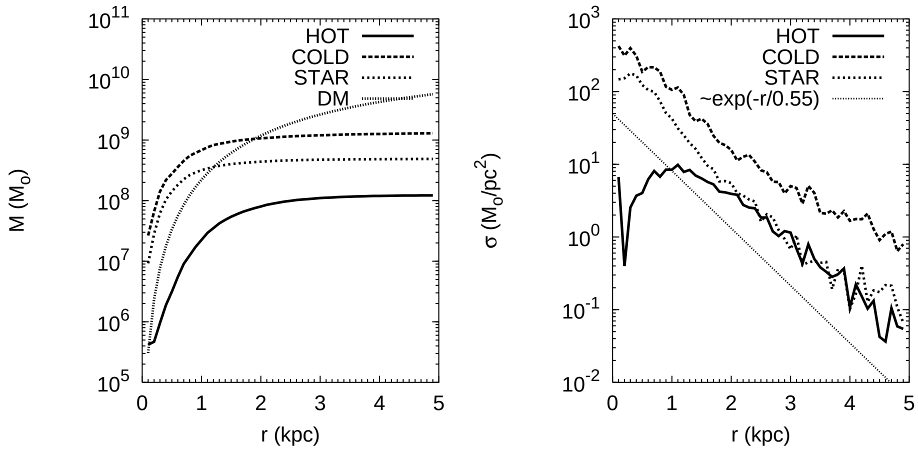

Figure 1: The radial distribution of the cumulative mass (left) and the surface density (right) for the different components in the central region of the model galaxy after 1 Gyr.

dark matter-gas-stellar systems (Navarro & White, 1993; Mihos & Hernquist, 1996). Nevertheless, until now the present codes lack of processes that are based on the coexistence of different phases of the interstellar medium (ISM), mainly dissipative, dynamical and stellar feedback, element distributions, etc. We have therefore developed a 3d chemodynamical code which is based on our single phase galactic evolutionary program (Berczik, 1999, 2000).

This code includes many complex effects such as a multi-phase ISM, cloud-cloud collisions, a drag force between different ISM components, condensation and evaporation of clouds (CE), star formation (SF) and a stellar feedback (FB). This code is a further development of our single phase galactic evolutionary program (Berczik, 1999, 2000) including now different gaseous phases. The more detailed description of the new code and the full list of the interaction processes between all gaseous and stellar phases will be presented in a more comprehensive paper by Berczik et al. (2002). Here we just briefly describe some basic features and effects.

In our new (multi-phase gas) code we use a two component gas description of the ISM (Theis et al., 1992; Samland et al., 1997). The basic idea is to add a cold (10^2 - 10^4 K) cloudy component to the smooth and hot gas (10^4 - 10^7 K) described by SPH. The cold clumps are modeled as N-body particles with

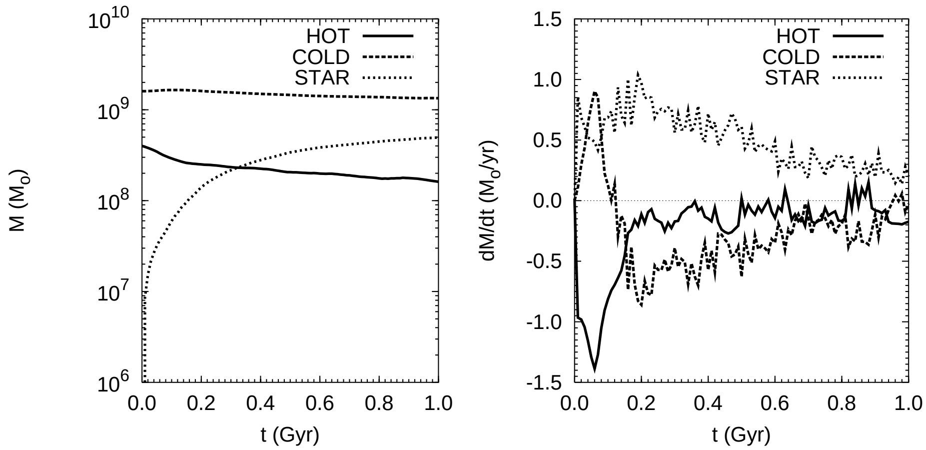

Figure 2: The temporal evolution of the mass (left) and mass exchange rate (right) for the different components of the model galaxy.

some "viscosity" (Theis & Hensler, 1993) (cloud-cloud collisions and drag force between clouds and hot gas component). The cloudy component interacts with the surrounding hot gas also via condensation and evaporation processes (Cowie et al., 1981; Köppen et al., 1998). In the code we introduce also star formation. The "stellar" particles are treated as a dynamically separate (collisionless) N-body component. Only the cloud component forms the stars. During their evolution, these stars return chemically enriched gas material and energy to both gaseous phases.

2. Basic ingredients of the code

For the parametric description of the cold clumps in the code we use the mass *vs.* radius relation for clouds based mainly on observations and also some theoretical work in this direction (Larson, 1981; Solomon et al., 1987; Maloney, 1990):

$$h_{\rm cl} \;\simeq\; 50 \;\cdot\; \sqrt{\frac{m_{\rm cl}}{10^6\ {\rm M}_\odot}} \quad {\rm pc}$$

This parameterization has already successfully been applied for the description of the cloudy medium of the ISM in Theis & Hensler (1993); Samland et al. (1997).

The basic mechanism for the mass exchange between "cold" and "hot" gaseous phases is a condensation *vs.* evaporation (CE) of the cold cloud clumps. In our code we follow the prescription of these processes using the model proposed in Cowie et al. (1981); Köppen et al. (1998). In this model the basic parameter controlling the process of CE is σ_0, which gives the ratio between a typical length scale of electron thermal conduction and the cloud size (compare also McKee & Begelman (1990); Begelman & McKee (1990)). If the cloud is small or has a high temperature the conduction length may exceed the cloud size ($\sigma_0 > 1$) and conductive evaporation is limited by saturation. On the other hand, if the temperature of the cloud becomes very small or its size very large, the cooling length scale becomes shorter than the cloud size and condensation substitutes evaporation. For simplicity and as in Cowie et al. (1981) we just use here $\sigma_0 = 0.03$ as transition value from evaporation to cooling, although a more detailed physical description should invoke the cooling or field length (McKee & Begelman, 1990; Begelman & McKee, 1990). In total the rate with which "cold" clouds evaporate to the surrounding "hot" gas their own material or acquire mass by condensation from the surrounding gas is

$$\frac{dm_{\rm cl}}{dt} = \begin{cases} 0.825 \cdot \mathrm{T}^{5/2}\, h_{\rm cl}\, \sigma_0^{-1} & \sigma_0 < 0.03 \quad \textbf{Condensation} \\ -27.5 \cdot \mathrm{T}^{5/2}\, h_{\rm cl}\, \Phi & 0.03 \le \sigma_0 \le 1.0 \quad \textbf{Evaporation} \\ -27.5 \cdot \mathrm{T}^{5/2}\, h_{\rm cl}\, \Phi\, \sigma_0^{-5/8} & \sigma_0 > 1.0 \quad \textbf{Saturated Evap}. \end{cases}$$

where we have used $\Phi = 1$ (no inhibition of evaporation by magnetic fields) and

$$\sigma_0 = \left(\frac{\mathrm{T}_{\rm hot}(\mathrm{K})}{1.54 \cdot 10^7} \right)^2 \frac{1}{\Phi\; n_{\rm hot}(\mathrm{cm}^{-3})\; h_{\rm cl}(\mathrm{pc})}$$

In our model the first important dynamical effect in the list of interaction between the two gaseous phases is a cloud dragging (DRAG). For this reason we use the prescription proposed in the papers Shu et al. (1972); Bisnovat'i-Kogan & S'un'aev (1972).

$$\frac{d\mathbf{p}_{\rm cl}}{dt} = C_{\rm DRAG} \cdot \pi h_{\rm cl}^2\, \rho_{\rm hot}\; |\, \mathbf{v}_{\rm cl} - \mathbf{v}_{\rm hot}\, |\; (\mathbf{v}_{\rm cl} - \mathbf{v}_{\rm hot})$$

The drag coefficient $C_{\rm DRAG}$ represents the ratio of the effective cross section of the cloud to its geometrical one $\pi h_{\rm cl}^2$ and is set to 0.5. A value of order unity for $C_{\rm DRAG}$ has the physically correct order of magnitude for the forces exerted by a pressure difference before and after a supersonic shock wave (Courant & Friedrichs, 1998).

The second important dynamical effect in the evolution of the cloudy medium is a cloud *vs.* cloud collisions (COLL). These processes also can significantly reduce the kinetic energy of the cloudy system. As a first approach for these processes we assume that in each collision the colliding clouds loss only 10 % of its kinetic energy.

Stars inject a lot of mass, momentum and energy (both mechanical and thermal) in the galactic system through Super Novae (SN) explosions, Planetary Nebula (PN) events and Stellar Wind (SW). The gas dynamics is then strongly depend on the star formation (SF) and a feed back (FB) processes.

Stars are supposed to be formed from collapsing and fragmenting cold gaseous clouds. Some possible SF criteria in numerical simulation have been examined (Katz, 1992; Navarro & White, 1993; Friedli & Benz, 1995). In our code we use the "standard" Jeans instability criterion inside the cloud particle, with randomized efficiency for SF. As a first step we select the cloud particles with:

$$h_{\rm cl} \; > \; \lambda_{\rm J} \; \equiv \; c_{\rm cl} \sqrt{\frac{\pi}{G \; \rho_{\rm cl}}}$$

After, we calculate the maximum SFR using the idea, what the whole Jeans mass $M_{\rm J}$ from the cloud convert to star particle during the $\tau_{\rm cl}^{\rm ff}$ time inside the Jeans volume $V_{\rm J}$:

$$\frac{d\rho_*^{\rm max}}{dt} \; \equiv \; \frac{M_{\rm J}}{\tau_{\rm cl}^{\rm ff} \; V_{\rm J}} \; = \; \frac{4}{3} \sqrt{\frac{6 \; G}{\pi}} \; \cdot \; \rho_{cl}^{3/2}$$

where: $\tau_{\rm cl}^{\rm ff} \; \equiv \; \sqrt{\frac{3 \; \pi}{32 \; G \; \rho_{\rm cl}}}$. The actual SFR in the each current act of SF we set by randomized these maximum SFR:

$$\frac{d\rho_*}{dt} \; = \; \textbf{RAND} \; (0.1 \; \div \; 1.0) \; \cdot \; \frac{d\rho_*^{\rm max}}{dt}$$

Every new "star" particle in our SF scheme represents a separate, gravitationally bound star formation macro region i.e. Single Stellar Population (SSP). The "star" particle is characterized its own time of birth $t_{\rm SF}$ which is set equal to the moment of particle formation. We assume that in the moment of creation the "star" particle, the individual stars inside our macro "star" particle distributed accordingly the Kroupa et al. (1993) Initial Mass Function (IMF).

During the evolution, these "star" particles return the chemically enriched gas to surrounding "gas" particles due to SNII, SNIa, PN events. As a first

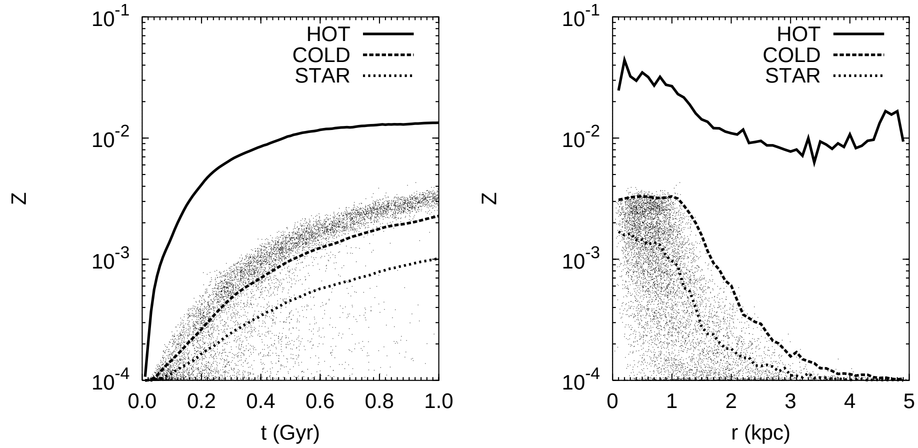

Figure 3: Temporal evolution of the metallicities (left) and their radial distribution after 1 Gyr (right). Individual metallicities of newly born stars are marked by dots.

approach, we consider only the production of ^{16}O and ^{56}Fe. The "star" particles return to ISM also the energy due to the SW, SNII, SNIa, PN processes. The total energy released by "star" particles calculated at each time step and distributed (in the form of thermal energy) between the neighbor ($N_B = 50$) "gas" particles.

The code also includes the photometric evolution of each "star" particle, based on the idea of the SSP (Bressan et al., 1994; Tantalo et al., 1996). At each time - step, absolute magnitudes: M_U, M_B, M_V, M_R, M_I, M_K, M_M and M_{BOL} are defined separately for each "star" particle. The spectro - photometric evolution of the overall ensemble of "star" particles forms the Spectral Energy Distribution (SED) of the galaxy.

3. Initial conditions

As a test of our new code, we calculate the evolution of an isolated star forming dwarf galaxy. The initial total gas content of our dwarf galaxy is 2×10^9 $M_\odot$ (80 % "COLD" + 20 % "HOT" which is placed inside a fixed dark matter halo with parameters $r_0 = 2$ kpc and $\rho_0 = 0.075$ $M_\odot/pc^3$ (Burkert, 1995). With these parameters the dark matter mass inside the initial distribution of gas (20 kpc)

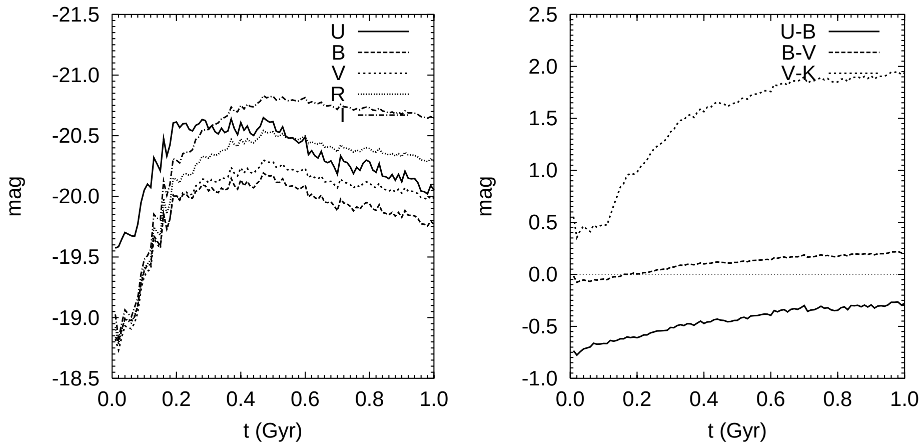

Figure 4: Temporal evolution of the model galaxy magnitudes in different spectral branch (left) and the color indexes (right).

is $\simeq\ 2\times10^{10}$ $M_\odot$. The initial temperatures for the cold gas we set 10^3 K, for the hot gas 10^5 K. For the initial gas distribution we use a Plummer-Kuzmin disk with parameters a = 0.1 kpc and b = 2 kpc (Miyamoto & Nagai, 1975). The gas initially rotates in centrifugal equilibrium around the z-axis.

We choose the dwarf galaxy as an appropriate object for our code, because in this case even with a relatively "small" number of cold "clouds" ($\sim 10^4$) we achieve the required physical resolution for a realistic description of individual molecular clouds ($\sim 10^5$ $M_\odot$) as a separate "`COLD`" particle. In the simulation we use $N_{hot} = 10^4$ SPH and $N_{cold} = 10^4$ "`COLD`" particles. After 1 Gyr more then 10^4 additional stellar particles are created.

4. First results

After a moderate collapse phase the stars and the molecular clouds follow an exponential radial distribution, whereas the diffuse gas shows a central depression as a result of stellar feedback Fig. 1. The metallicities of the galactic components behave quite differently with respect to their temporal evolution as well as their radial distribution Fig. 2. Especially, the ISM is at no stage well mixed.

In Fig. 1. we present the mass and surface density distribution of the different components in the central region of the model after 1 Gyr of evolution. In the region up to ≈ 2 kpc the baryonic matter dominates over the DM. The surface density of the stars can be well approximated by an exponential disk with a scale length of 0.55 kpc. In the distribution of hot gas, we see a central "hole" ($\approx$ 1 kpc), as a result of gas blow-out from the center mainly due to SN explosions but not for the cold gas. This results disagrees with the model by Mori et al. (1999) where a density hole occurs caused by their single gas-phase treatment.

In Fig. 2. we present the evolution of the mass and the mass exchange rate of the different components. The SFR (i.e. dM_{STAR}/dt) peaks to a value of 1 $M_\odot yr^{-1}$ after 200 Myrs. Afterwards it drops down to 0.2 $M_\odot yr^{-1}$ within several hundred Myrs. I.e. that after 1 Gyrs the stellar mass has already reached 5×10^8 $M_\odot$. Another interesting feature is the behaviour of the hot gas phase mass exchange. After the initial violent phase of condensation an equilibrium is established which gives a hot gas fraction of about 10% of the total gas mass.

The metal content of the diffuse gas and the clouds differs significantly over the whole integration time (Fig. 3.). Due to SNII and SNIa events the metallicity of the hot phase exceeds that of the clouds by almost one order of magnitude. The clouds mainly get their metals by condensation of the hot phase. The central metallicity plateau (up to 1 kpc) of the cold component is explained by the fact, that condensation of metal-enriched material does not work efficiently in that region. This signature agrees well with the observed abundance homogeneity in dIrrs over up to 1 kpc (e.g. in I Zw 18: Izotov (1999)). Moreover, the conditions in the center lead mainly to evaporation of clouds which also prevents the mixing with the metal enriched hot gas.

In the Fig. 4. we present the evolution of the model galaxy magnitudes in different spectral branch and also the color indexes.

Acknowledgements

The work was supported by the German Science Foundation (DFG) with the grants 436 UKR 18/2/99, 436 UKR 17/11/99 and the SFB439 (subproject B5) at the University of Heidelberg. P.B. is grateful for the hospitality of the Astronomisches Rechen-Institut (Heidelberg) where the main part of this work has been done. The calculation has been computed with the `GRAPE5` system at the Astronomical Data Analysis Center of the National Astronomical Observatory, Japan. R.Sp. acknowledges support by the German-Japanese cooperation grant 446 JAP 113/18/0-2.

References

Begelman M.C. & McKee C.F., 1990, ApJ, 358, 375

Berczik P., 1999, A&A, 348, 371

Berczik P., 2000, Ap&SS, 271, 103

Berczik P., Hensler G., Theis Ch. & Spurzem R., 2002, A&A, in prep.

Bisnovat'i-Kogan G.S. & S'un'aev R.A., 1972, SvA, 16, 201

Bressan A., Chiosi C. & Fagotto F., 1994, ApJ, 94, 63

Burkert A., 1995, ApJ, 447, L25

Courant R. & Friedrichs K.O., 1998, in "Supersonic Flow and Shock Waves" (Appl. Math. Sciences Vol. 21), Springer-Verlag Berlin Heidelberg, p. 325

Cowie L.L., McKee C.F. & Ostriker J.P., 1981, ApJ, 247, 908

Friedli D. & Benz W., 1995, A&A, 301, 649

Izotov Y.I., 1999, Proc. XVIII. Rencontre de Moriond, Les Arc, *Dwarf Galaxies and Cosmology*, eds. T.X.Thuan et al., Edition Frontiere, Gif-sur-Yvette

Katz N., 1992, ApJ, 391, 502

Kroupa P., Tout C. & Gilmore G., 1993, MNRAS, 262, 545

Köppen J., Theis Ch. & Hensler G., 1998, A&A, 331, 524

Larson R.B., 1981, MNRAS, 194, 809

McKee C.F. & Begelman M.C., 1990, ApJ, 358, 392

Maloney P., 1990, ApJ, 349, L9

Mihos J.C. & Hernquist L., 1996, ApJ, 464, 641

Miyamoto M. & Nagai R., 1975, PASJ, 27, 533

Monaghan J.J., 1992, ARA&A, 30, 543

Mori M., Yoshii Y. & Nomoto K., 1999, ApJ, 511, 585

Navarro J.F. & White S.D.M., 1993, MNRAS, 265, 271

Samland M., Hensler G. & Theis Ch., 1997, ApJ, 476, 544

Shu F.H., Milione V., Gebel W., Yuan C., Goldsmith D.W. & Roberts W.W., 1972, ApJ, 173, 557

Solomon P.M., Rivolo A.R., Barrett J. & Yahil A., 1987, ApJ, 319, 730

Tantalo R., Chiosi C., Bressan A. & Fagotto F., 1996, A&A, 311, 361

Theis Ch., Burkert A. & Hensler G., 1992, A&A, 265, 465

Theis Ch. & Hensler G., 1993, A&A, 280, 85